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The Impact of the Women of the Technical Section of the Admiralty Air Department on the Structural Integrity of Aircraft during World War One

October 23, 2018

Abstract:

In 1917, as the air war raged in Europe, some of Britain's finest mathematicians, engineers and scientists engaged in their own battle to understand the fundamentals of aerodynamics and aircraft construction. In London, Wing Commander Alec Ogilvie led the Technical Section of the Admiralty Air Department, which included a number of individuals dedicated to addressing aircraft structural issues; amongst them were three women, Hilda Hudson, Letitia Chitty and Beatrice Cave-Browne-Cave. In this article I describe the aeronautical landscape in Britain during the second decade of the 1900s, the place of these women within it, and their contributions to the structural integrity of early, British military aircraft.

Estratto:

Nel 1917, mentre in Europa infuriava la guerra aerea, alcuni tra i migliori matematici, ingegneri e scienziati britannici combattevano per carpire i principi dell'aerodinamica e della costruzione aeronautica. A Londra il Tenente Colonnello Alec Ogilvie dirigeva la Sezione Tecnica del Dipartimento aereo dell'Ammiragliato, che includeva un gruppo di persone dedicate alle problematiche strutturali dei velivoli. Tra queste vi erano tre donne: Hilda Hudson, Letitia Chitty and Beatrice Cave-Browne-Cave. In questo articolo descrivo il panorama aeronautico durante la seconda decade del 1900, il ruolo di queste donne all'interno in quell'epoca e il contributo che hanno apportato all'integrità strutturale della prima aeronautica militare britannica.

MSC: 01A60

Keywords: Aeronautics; Women mathematicians; World War One; Structural analysis.

1 Introduction

In 1909, Richard Burdon Haldane, British Minister for War, viewed developments in aviation with interest, conscious that the revolutionary heavier-than-air machines would undoubtedly be key participants if, as seemed likely, hostilities commenced in Europe. He considered it prudent, therefore, to engineer a measure of control over the rather disparate band of aeronautical protagonists who had emerged during the previous decade. Consequently, on the 30th April of that year, he formally established the Advisory Committee for Aeronautics (ACA), a body of men that would orchestrate the early evolution of British aviation. Louis Blériot's historic flight in his Type XI aircraft across the Channel less than three months later brought Haldane's prescience into sharp focus, as it became apparent to most that Britain could no longer hide behind its impressive navy; to remain impervious to the threat from the air would be folly.

The potential importance of the ACA was clear, so Haldane knew its leader had to be someone with established credentials; an obvious candidate, a man with gravitas and credibility in abundance, was John Strutt. Better known as Lord Rayleigh, Strutt was a heavyweight in contemporary science and mathematics, already regarded as a world authority in the field of acoustics following publication of his two-volume work, *The Theory of Sound* (Lord Rayleigh, 1877, 1896); he was also a Nobel Laureate.¹ He had indicated his personal interest in aeronautics as early as 1891, authoring a review in *Nature* (Lord Rayleigh, 1891) of Langley's *Experiments in Aerodynamics* (Langley, 1891). His subsequent delivery in Manchester of the Wilde lecture in 1900 entitled *The Mechanical Principles of Flight* (Lord Rayleigh, 1900) updated his credentials and this, combined with his experience in hydrodynamics, gave him the perfect résumé.² In fact Rayleigh would become the driving force behind the discontinuity theory of aerofoil lift, championed by Britain until the post-war era, when the circulatory theory, most associated with the German engineer Ludwig Prandtl, was seen to reflect a much closer representation of reality.³ Interestingly, Frederick Lanchester (1868-1946) had been arguing the merits of a circulatory component in theoretical lift analysis for years, but this solitary British voice was lost amidst the noise in support of Rayleigh's penchant for the alternative.⁴

Someone taking a macroscopic view of aeronautics in Britain at the start of the

¹ Rayleigh received the Nobel Prize for Physics in 1904 in recognition of his discovery of the noble gas, argon, in 1894.

² The Wilde lecture was named after Henry Wilde, F.R.S., electrical engineer and President of the Manchester Literary and Philosophical Society, 1894-1896.

³ The discontinuity theory's origins in this context dated back to Rayleigh's 1876 paper *On the Resistance of Fluids* in which he notes when talking of a flat lamina at an angle to a water flow that, "Behind the lamina there must be a region of dead water bounded by a surface of discontinuity, within which the pressure is the same as if there were no obstacle. On the front face of the lamina there must be an augmentation of pressure ..." (Lord Rayleigh, 1876, 434). The circulatory theory of lift argued that the presence of an aerofoil in an airflow induced a circulation of air around it which modified the normal flow in a way that reduced pressure on the top surface whilst increasing it on the lower. See Bloor's *Enigma of the Aerofoil* (Bloor, 2011) for a comprehensive discussion of this dichotomy.

⁴ Lanchester had actually postulated a circulatory explanation for lift in his book *Aerodynamics* (Lanchester, 1907), but a perceived lack of rigour in his mathematics, coupled with his engineering background, made Rayleigh's offering more plausible.

second decade of the 20th century would have witnessed a veritable potpourri of influences; that said, broad delineation is possible: the Royal Balloon Factory, the National Physical Laboratory (NPL), industry, academia, and the Admiralty, were all salient players. Faced with this rather eclectic fellowship, it made sense for Rayleigh to source the members of his committee, reasonably evenly, from the aforementioned. We thus see Mervyn O’Gorman and Richard Glazebrook chosen to represent the two research establishments, Frederick Lanchester and Arnulph Mallock co-opted from industry, academics such as Alfred Greenhill (who had recently retired from the Royal Military Academy) and Joseph Petavel from Manchester University, and, inevitably, representatives from the Army and Navy to reflect the burgeoning military interest in aviation. The new Advisory Committee would sit at the heart of British aviation to control, guide, and coordinate efforts until after the War, when it morphed into the Aeronautical Research Committee; a homogeneous evolution.

Before discussing the women central to this story, it is important to understand the context of their journeys into the world of aeronautics. A closer look at the prominent features and functions of the aeronautical landscape will be our starting point.

1.1 The Royal Aircraft Factory

The Royal Aircraft Factory (RAF) at Farnborough was the jewel in the crown of the ACA. The Factory went through something of an identity crisis during the immediate pre-war years; the Royal Balloon Factory, as it was known in 1909, became the Army Aircraft Factory in 1911 before completing its metamorphosis into the RAF in 1912. Its main purpose in its latter guise was to be a source of innovation in design in aeronautics and a primary research establishment, working in parallel with the NPL. Despite the name changes, the balloon facility remained in situ under the supervision of Colonel John Capper, but it was the key appointment by the ACA towards the end of 1909 of Mervyn O’Gorman as Superintendent to lead the departure into fixed-wing aircraft development that would prove incisive. The electrical engineer, who learnt his trade at the City and Guilds Central Institution, London, brought industrial experience, scientific insight, and clear vision to the role.⁵

O’Gorman faced significant challenges in building the foundations of Britain’s primary, fixed-wing, aeronautical research centre. Fortunately, coinciding with his arrival at Farnborough however, help was soon at hand in the person of design engineer, Fred Green.⁶ A serendipitous reunion at the 1910 Aero Show in London between Green and old friend, pioneering aircraft designer and pilot, Geoffrey de Havilland, soon brought the latter into the fold, and the new team set to work to improve upon the performance and design of the first prototype

⁵ The City and Guilds of London Institute for the Advancement of Technical Education was founded in 1876 by sixteen of the City of London’s livery companies and eventually, in 1893, became Finsbury Technical College, recognised as the first Technical College in England.

⁶ Green had cut his teeth working as an engineer in the early British motor trade. His specialization was engine design, something he continued developing in the aeronautics/motor industry with the Siddeley-Deasy Company, following his departure from the RAF in 1916.

aircraft that had flown at Farnborough in 1908, the rather insipidly-named *British Army Aircraft Number 1*.⁷ It wasn't long before the collaboration had designed, built and tested a new prototype, and by March 1912, its second iteration, the B.E.1 (Blériot Experimental 1), emerged; by August of the same year, the B.E.2 variant appeared.

In the Summer of 1912, O'Gorman's tour de force was enticing an academic from Cambridge, who had been awarded a degree in the First Class in the Mechanical Sciences Tripos and who was also a qualified pilot, to join the group. Edward (Ted) Teshmaker Busk (1886-1914) was given the title Assistant Engineer Physicist, and he immediately began coordinating tests on de Havilland's B.E.2a, as it was now designated. Busk mainly worked in the office, making sense of the experimental results fed to him by the pilots nominated to fly the test profiles, but he soon became frustrated by the lack of empathy that these men demonstrated regarding what he was trying to achieve. In March of 1913, he convinced O'Gorman that the only solution was for him to conduct his own experiments, and so he became de Havilland's protégé to learn the rudiments of test flying.⁸ In the previous year George Bryan (1864-1928) had published his seminal work *Stability In Aviation* (Bryan, 1911), and Busk was able to take Bryan's theory, understand it, and then set to work producing a design for a stable aircraft. The fruit of his labour was the R.E.1 (Reconnaissance Experimental 1) which he first flew in the Spring of 1913 and which is widely considered to be the first inherently stable aircraft ever constructed; it would be the forerunner of the B.E.2c, one of Britain's aviation workhorses during the early part of the War.

It is worth reflecting here that whilst Busk went about his work there was still no agreed theory to describe what made these contraptions, held together by bits of string and canvas, fly at all. Somehow he had managed to construct a machine that would not only fly but that also possessed, arguably, the most important intrinsic characteristic (certainly of a reconnaissance aircraft), that of stability in flight. What a tragedy, then, that the man capable of such wizardry would perish barely eighteen months later when his B.E.2c burst into flames above Farnborough.⁹ His impact at the RAF went deeper than just a brilliant feat of engineering though; he had set a precedent. Here was a graduate of King's College, Cambridge, who had combined his academic prowess and industrial experience with flying skills to produce something of practical worth in the field of aeronautics; a mathematically-based academic training melding with genuine engineering.

⁷ The aircraft's official maiden voyage on 16th October 1908 saw Samuel Cody travel 463 yards across the Hampshire airfield before crashing during an attempted turn.

⁸ Busk attended the A.S.L. School of Flying in early 1912. Founded in 1909, A.S.L. (Aeronautical Syndicate Limited) was one of the first aeroplane manufacturing companies in Britain; it diversified into flying training in 1910, based at the Hendon aerodrome in north-west London. At that time, flying licences (known as 'Aviators' Certificates') were issued by The Royal Aero Club. Busk's graduation from the school at Hendon coincided with the formation of the Central Flying School at Upavon, Wiltshire, which then assumed responsibility for military flying training; prior to this, the military had delegated all its pilot training to the civilian sector.

⁹ It is believed the cause of the fire in Busk's machine was a spark from the engine that ignited fuel that had come from the overflow pipe in the front fuel tank and pooled on the cockpit floor.

Prior to leaving the RAF at the end of his seven-year contract, O’Gorman had put together a team capable of unlocking the mysteries of flight and advancing knowledge in this fledgling field. Some of this cohort had been drawn into aeronautics on its own merits and would go on to make careers out of it, whereas others were co-opted by the morbid necessities of war and would return to pursue their true passions once peace had been brokered; those who survived, of course.¹⁰ By the time Henry Fowler replaced O’Gorman as Superintendent in 1916, there was assembled at Farnborough some of Britain’s finest mathematical and engineering minds.¹¹

From its humble beginnings the RAF would blossom into the keystone of the ACA’s asset portfolio. Not only would it thrive in aircraft Research and Development and associated construction, it would also mass-produce its most successful designs, much to the annoyance of the privateers, who thought this very much to be treading on their territory.¹² The importance of the Factory was also reflected in the size of its workforce which, by the end of the War, exceeded 5000, 1500 of whom were women.¹³

1.2 The National Physical Laboratory

The NPL at Bushy House, Teddington, was established in 1900 to set standards in science and engineering. Various rumblings and statements of intent had been made at a number of British Association meetings during the 1890s as unease grew at Germany’s advantage in this field, and so the arrival of the British equivalent of the Physikalisch-Technische Reichsanstalt, established in the mid 1880s, was long overdue. The likes of Werner von Siemens and his successors had been driving Germany forward for well over a decade, and it was time for a British response. Initially the Technical Societies dictated the specializations at the Laboratory; mechanics and engineering, electricity, optics, chemistry, metrology, terrestrial magnetism and thermometry were the chosen demarcations. As time passed, however, the remit broadened and, in 1909, the Aeronautical Division appeared, coinciding with the formation of the ACA. The man given the responsibility for running the NPL was Richard Glazebrook.

The Trinity-educated mathematician and physicist had graduated as fifth Wrangler in 1876 and had close links with Rayleigh (himself the Senior Wrangler in

¹⁰ A number of the mathematicians and engineers who followed Busk also became pilots or observers to enable better airborne experimentation using full-scale aircraft; many perished in this pursuit, most notably, D.H. Pinsent, H.A. Renwick, and K. Lucas. In August of 1918, Bertram Hopkinson, Professor of Mechanism and Applied Mechanics at Cambridge, became another significant casualty when his Bristol Fighter crashed near London in severe weather.

¹¹ The core group at the RAF became known as the *Chudleigh lot* (named after the house in which they messed) and comprised G.I. Taylor, G.P. Thomson, B.M. Jones, F.A. Lindemann, G.T.R. Hill, R. McKinnon Wood, K. Lucas, F.W. Aston, H. Glauert, W.S. Farren, D.H. Pinsent and H. Grinstead (Thomson and Hall, 1971, 217).

Henry Fowler had been Chief Mechanical Engineer for the Midland Railway prior to his war appointment at the RAF.

¹² O’Gorman left the RAF rather abruptly, having been held responsible for performance issues with the B.E.2c, and over the controversy surrounding the RAF’s role in mass-producing aircraft and aero-engines.

¹³ See Barrow-Green’s contribution to Aubin and Goldstein (Aubin and Goldstein, 2014, 80).

1865) through their collaboration at the Cavendish Laboratory, so his appointment to the Bushy House post was no surprise.¹⁴

The new Aeronautics Division fell under the umbrella of Thomas Stanton's Engineering Department and was headed by Leonard Bairstow (1880-1963), who was well on his way to establishing himself as one of the most influential and important British characters in early aerodynamic research.¹⁵ He had served his mathematics and engineering apprenticeship under John Perry at the Royal College of Science (RCS) in London, and was the leading experimentalist in the field of aircraft stability and great advocate of the wind tunnel as a source of reliable data.¹⁶ Turning down Glazebrook's offer of the Superintendent's position of the proposed new Aerodynamics Department in 1917, Bairstow instead took up a post at the Air Board under Alec Ogilvie (1882-1962), (see Section 1.5).¹⁷ It was here that he engaged in the co-ordination of work pertaining to the structural strength of aircraft, thus taking his place in the mosaic of this narrative.

Since women in mathematics and engineering is the focus of this article, it is apposite to note the recollection of a research assistant, C.H. Burge, regarding the appointment of the first women at the Laboratory, who apparently "aroused curiosity" and were generally employed testing compasses and shell gauges.¹⁸ As the demands of the War increased, however, their roles necessarily became more diverse. Joseph Petavel, who replaced Glazebrook as Director in 1919, would deliver a hammer blow to equality in the post-war era though by openly stating that no more women would be employed at the NPL on his watch, using the excuse that he felt their tenure in scientific work was much too uncertain.

¹⁴ At Cambridge University, 'Wrangler' was the name given to a student placed in the First Class of the Mathematical Tripos. The 'Senior Wrangler' was the student placed top of the Wrangler list based on his academic performance, and the title brought with it high esteem, both within University circles and in wider society.

The Cavendish Laboratory opened in 1874 in Cambridge under James Clerk Maxwell. Rayleigh took the helm as Cavendish Professor of Experimental Physics in 1880 following Maxwell's premature death. Glazebrook, appointed as a demonstrator at the Laboratory in the same year, hoped to succeed Rayleigh, but J.J. Thomson prevailed in the 1884 election despite Rayleigh's overt support for Glazebrook.

¹⁵ Stanton had been Professor of Engineering at Bristol University prior to his appointment at the NPL.

Harold Roxbee Cox, a post-war expert on aeroelasticity, apparently suggested in a mischievous moment that the roof of the large wind tunnel (known in those days as a 'wind channel') at Farnborough should be decorated with statues of all the great pioneers of aeronautics from "Leonardo da Vinci to Leonardo da Bairstow" (Temple et al., 1965, 31)!

¹⁶ Perry was Professor of Mechanics and Mathematics at the RCS and was the driving force behind the 'Perry Movement' that championed reform in the mathematical education of engineers during the early 1900s.

¹⁷ The new status of 'Department' reflected the increasing size and importance of the aerodynamics element of the NPL's work.

¹⁸ Burge was an assistant in the Aeronautics Division at the NPL during the early days of research, initially testing balloon fabrics with Arthur Fage, the first person to study the aeroelastic phenomenon of aircraft 'flutter'. Burge's observation was taken from his contribution to a document looking back over the first 70 years of the NPL (Burge, 1970, 24).

1.3 Industry

Industry identified a lucrative market opening up and so many aeronautically-enlightened entrepreneurs moved to take advantage; individuals who later would become household names such as Shorts, Handley-Page and Sopwith. Typical of this genre of businessman was Richard Fairey (1887-1956). Perhaps it was the proud family heritage in the carriage-building trade that lay at the heart of his inspiration, but one suspects it was the guiding hand of Silvanus Thompson at Finsbury Technical College that cajoled the young Fairey into the world of engineering.¹⁹

Fairey's link to aeronautics came in 1910 when the 22-year-old Londoner inadvertently infringed a patent registered to J.W. Dunne whilst competing in a model aeroplane competition at Crystal Palace.²⁰ This provoked a bipartite meeting and his subsequent appointment in 1913 as chief engineer at Shorts Brothers, who were at the vanguard of the trade. Two years later, Commodore Murray Sueter, one of the military representatives on the original ACA, would convince Fairey to set up his own firm.²¹ The industrial aeronautical development at this time is a fascinating story in itself, but not the focus here, suffice to say that by 1915 over 30 companies were engaged in aeronautical work and, by the end of the War, the industry employed nearly 350,000 people in Britain.²²

1.4 Academia

A number of Britain's universities and colleges also became involved as aeronautics raised its profile during the immediate pre-war period; indeed by 1909, the aeronautical genre was beginning to be recognized in its own right as an important branch of engineering. As the NPL set up its dedicated group, so too did the East London College (now Queen Mary University of London) under A.P. Thurston (1881-1964).²³ Imperial College began a scholarship programme

¹⁹ S.P. Thompson was Principal and Professor of Physics at Finsbury Technical College for 30 years (1878-1908) and was a great proponent of technical education as a means of converting science into practical engineering.

²⁰ John Dunne, a Second Lieutenant in the Army, was intimately involved with secret flight trials held at Blair Atholl in the Scottish Highlands in 1907 and 1908 using some of his glider and aircraft designs. He had become interested in aeronautics during a period of sick leave and began a more formal association with the field when appointed to a post at the Royal Balloon Factory in 1906. In many ways Dunne's distinctive 'V-shaped' wings were prophetic of modern-day lifting surfaces. A fitting tribute to Dunne's work appeared in a 1943 edition of *Flight* (Poulsen, 1943).

²¹ For a more comprehensive discussion of Fairey's life, see Professor Adrian Smith's ongoing research project at the University of Southampton entitled *The life of Sir Richard Fairey (1887-1956), aircraft designer and industrialist* (Smith, 2016).

²² Fearon offers a concise summary of the industrial expansion in British aeronautics in his piece, *The Formative Years of the British Aircraft Industry, 1913-1924* (Fearon, 1969).

²³ Thurston, a graduate in Mechanical and Electrical Engineering from East London College in 1906, had returned to his alma mater to set up the first aeronautical engineering department in Britain in 1909. He gave lectures on the subject and is credited with a significant role in the development of the first leading-edge devices for wings ('slats' in modern-day parlance). 1913 saw Thurston awarded the first ever D.Sc. (a qualification introduced in 1860 by London University to reflect advanced study) for aeronautical research and, after adding a flying licence to his qualifications, he was given responsibility for the safety design requirements and structural integrity testing of military aircraft for

allowing talented students of mathematics, engineering and physics to take on work under Bairstow at the NPL; Arthur Fage, mentioned earlier (see footnote 18) who arrived at the NPL in 1912, was a typical example of such a student. Lectures in aeronautics also began at Imperial, spearheaded by the high-profile visiting lecturer, George Greenhill.²⁴ At University College, London (UCL), in 1916, as the demands of war permeated through the fabric of British life, Karl Pearson's cell of human computers was eased away from analysis of national statistics to pursue more war-applicable endeavours.²⁵ Manchester, too, forged ahead with relevant research, particularly in the field of fluid dynamics, with the Osborne Reynolds Laboratory being used exclusively for the inspection and calibration of aircraft instruments throughout the period of conflict. Even Cambridge turned a hesitant gaze skywards. It wouldn't be until after the War, however, that the universities really started investing heavily in this sector, Cambridge in particular developing an important school of aviation research under Bennett Melvill Jones (1887-1975).²⁶

1.5 The Admiralty in 1917

Militarily, command and control of aerial assets was centred at the Admiralty in London, and while Sir David Henderson pondered the amalgamation of the Royal Flying Corps and Royal Naval Air Service, the important business of ensuring the structural integrity of Britain's military aircraft continued apace. The rapidly changing dynamics of the conflict in terms of air power ensured that the organisational structure of the Admiralty during the latter years of the War was in a state of flux and, with over 10,000 assorted military ranks and civilian employees concentrated in London, it must have been a frantic and challenging environment in which to be applying mathematics. Our focus here will be to consider the impact that three particular women had on the effort to make early British-designed aircraft as structurally sound as possible.

Working in the structures subdivision of the Technical Section, Hilda Hudson (1881-1965), Letitia Chitty (1897-1982), and Beatrice Cave-Browne-Cave (1874-1947) plied their trade in their offices located in the Hotel Cecil, just off The Strand, in the very heart of the capital. Before considering their individual contributions in detail, however, it is worth noting some of the other influential

the duration of the War.

²⁴ Greenhill, second Wrangler in 1870, had been the Professor of Mathematics at the Royal Military Academy, Woolwich, for over 30 years before bringing his knowledge of aerodynamics, gained whilst preparing his work *Dynamics of Mechanical Flight* (Greenhill, 1912), to Imperial.

²⁵ Doyen of mathematical statistics, Pearson was third Wrangler in 1879, and spent much of his academic career at UCL, where he held the Chair of Applied Mathematics and Mechanics. See Barrow-Green (Barrow-Green, 2015) for details of the role of Pearson and the Galton Eugenics Laboratory staff during the War.

²⁶ Jones had been a student of the influential Bertram Hopkinson at Cambridge and was a close friend of Ted Busk, both of whom perished in the flying accidents previously discussed. He worked on the development of aircraft instrumentation and gunnery during the War, and his experience and background at the NPL, RAF, and as a pilot, led to his appointment as the first Francis Mond Professor of Aeronautical Engineering at Cambridge in 1919, the professorship named in honour of the Peterhouse graduate who lost his life whilst flying with the Royal Air Force on the Western Front.

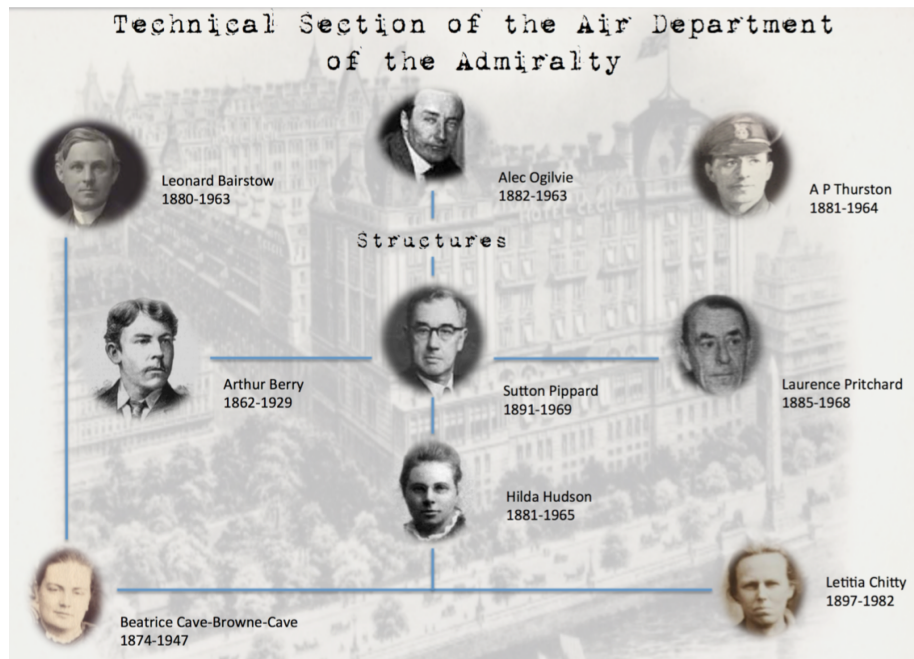


Figure 1: The Technical Section of the Air Department of the Admiralty - 1917

characters surrounding them. Whilst not a comprehensive reflection of those present, Fig. 1 illustrates where the women sat in the hierarchy in 1917.²⁷

Wing Commander Alec Ogilvie was the Controller of the Technical Section. He had a pedigree in aviation, being only the seventh person in Britain to hold a pilot's licence, and a pioneering competitor in the early air races.²⁸ His technical pursuits resulted in the production of an early type of airspeed indicator, and his impressive curriculum vitae would prove to be a future passport into an important leadership role when Royal Air Force formed in 1918. Leonard Bairstow operated as the master overseer, co-ordinating efforts across the various technical disciplines of structures, aerodynamics, performance, and airscrews (propellers); he appeared to have more direct access to Cave-Browne-Cave than to the other women.²⁹ Thurston's status was similar to Bairstow's, but his remit was more safety and testing. He officially occupied the seat below the Controller, but Ogilvie's second-in-command in structures was, in any practical sense, Sutton Pippard (1891-1969) (see Section 4.4). Arthur Berry (1862-1929) and Laurence Pritchard (1885-1968) completed a formidable triumvirate in this stratum, Berry's prowess in mathematics working in perfect harmony with the engineering insight and experience of the other two men.³⁰

²⁷ (Skempton, 1970, 466) indicates that there were about 20 people working in the structures office by 1918.

²⁸ Ogilvie was placed third in the *Gordon Bennett* air race of 1910 flying a Wright Model R, and backed this up with a fourth place the following year.

²⁹ Cave-Browne-Cave is known to have been paired-up with Eleanor Lang, who had graduated with an MA in Mathematics from UCL in 1911. In the words of Chitty, the two were Bairstow's "devoted assistants" (Chitty, 1966, 67).

³⁰ See footnote 65.

Then came the women: Hudson, their chef d'équipe; Cave-Browne-Cave; and the relative youngster, Chitty. Hudson arrived directly from a teaching post, and Chitty from university, but Cave-Browne-Cave trod a more vexed path, working for Karl Pearson at the Department of Applied Statistics at UCL before leaving under somewhat acrimonious circumstances to take up her post at the Admiralty with Bairstow.³¹ The Bairstow/Cave-Browne-Cave partnership strengthened and flourished both during and after the War; Chitty equally forged a strong working relationship with her mentor, Pippard, a bond that the pair would subsequently exploit in the inter-war years.

2 The Environment for Women

We now have some appreciation of where these women sat in the big scheme of British aeronautics in 1917, but what of the nature of the environment defining their individual journeys to London?

As young women, society did not particularly encourage them to have aspirations to succeed in the fields of mathematics and engineering; these were very much considered exclusive domains of the male. Indeed few schools were even willing to teach girls to a sufficiently high standard in mathematics to enable them to pursue the subject further at university, so private tuition was invariably the only practical way forward.

For those few managing to gain acceptance into a college such as Girton or Newnham at Cambridge, their relative lack of preparedness made them unattractive candidates in the general mêlée to secure the best tutors, so their coaching was often, although not exclusively, inferior, as was their general status.³² Indeed at Cambridge, it had only been since 1880 that women were offered the opportunity to sit the Tripos examinations, Charlotte Angas Scott the pioneer.³³ Despite Scott's breakthrough, however, by virtue of their non-degree status, it remained impossible for women to appear in the same ranking list as the men; they could only be referenced by the position they would have held had they been on the list.³⁴ It would actually be 1948 before this disparity was addressed at Cambridge, although Oxford (1920) and London (1878) were more progressive.

³¹ See (Porter, 2010, 274).

Pearson encouraged a link with Girton College, Cambridge, to provide mathematically gifted women with an opportunity to work on statistical analysis at UCL; Beatrice's younger sister and fellow Girton alumna, Frances (1876-1965), who had been placed in the third division of the First Class of the Mathematical Tripos in 1899, was one of the first to take advantage, co-authoring works with Pearson such as *On the Correlation between the Barometric Height at Stations on the Eastern Side of the Atlantic* (Cave-Browne-Cave and Pearson, 1902).

³² Students would employ the services of a coach, at extra expense, to supplement the general instruction being provided by the university and college lecturers.

³³ Charlotte Scott, alumna of Girton College, went on to become Professor of Mathematics at Bryn Mawr College in Pennsylvania, and established a strong conduit for aspirational female mathematicians between Britain and the USA.

³⁴ Women were not awarded degrees, the primary aim of the policy being to deny women any voting rights in university elections.

Regarding future employment prospects, these were clearly limited by the complete male dominance in virtually all spheres of mathematics and engineering other than perhaps school teaching which, unsurprisingly, was a profession in which all three of our women were employed at some point during their lives.

So the general status and realistic chances of a successful career for women who had studied university-level mathematics was poor at best. Hardly surprising, then, that the frustration felt in general amongst many women was beginning to manifest itself in more demonstrable ways as the Suffragette movement gained momentum. Societal challenges aside, however, what technical challenges were facing Hudson, Chitty and Cave-Browne-Cave when they arrived at the Admiralty; what was the nature of their employment?

3 Structural Problems

Data for causes of structural failure of aircraft during the early part of the 1900s are elusive, but there is no doubt that a problem existed. What we now call aeroelastic forces were not fully understood or appreciated in the early days of aviation, and the application of mathematics to solve aeronautical engineering problems was in a transitional phase, as the established mechanics of solid, ground-based structures was rapidly being modified to apply to the more dynamic, subtle and often unpredictable demands of an aircraft in flight.

One of the initial deliberations of the ACA in this respect concerned load factor; how much ‘g’-force should an aircraft be designed to withstand?³⁵ The answer was given in the 1913-14 *Technical Report of the ACA* (Lord Rayleigh, 1915) as six ‘g’. As the War progressed and the roles of aircraft became more diverse, common sense prevailed, and the load factor for larger machines such as the Handley Page O/400 bomber was reduced to three ‘g’; the weight penalty of greater strength would have been practically prohibitive given the modest horsepower of the available aero-engines.

In terms of aircraft design, it was structural integrity that in many ways was responsible for the preponderance of biplanes. The box-like nature of the double wing with its struts and wires helped prevent wing distortion due to aerodynamic forces. It was also a configuration that lent itself to structural analysis that was not dissimilar to that pertaining to something such as a box girder bridge.

One of the most frightening phenomena experienced by some early aircraft was that of ‘flutter’. This was an aeroelastic effect that created oscillations in wing or fuselage structures that could lead to potentially catastrophic twisting forces. The first study into this effect was published in 1916 in the *Reports and Memoranda (R. & M.) of the ACA* (Fage and Bairstow, 1920);³⁶ it was an investigation that would eventually lead to Cambridge mathematician, Robert

³⁵ An aircraft experiences a force of one ‘g’ vertically downwards whilst on the ground or in straight, level, unaccelerated flight. When manoeuvring in flight, or when subjected to certain meteorological phenomena, any resulting force experienced by the aircraft and occupant(s) can be expressed as a multiple of the one ‘g’ datum.

³⁶ For a discussion of the circumstances prompting this investigation see (Collar, 1978, 38).

Frazer (1891-1959), pioneering the application of matrix techniques to engineering problems.³⁷

Destructive testing was also a technique that was being used to improve structural integrity, and Albert Thurston played a key role. Original papers exist that detail his team's tests on early aircraft such as the D.H.4 and Bristol Biplane.³⁸ Many of the stress loading tests on wings were actually performed at Farnborough using aircraft turned upside-down. Sand bags were placed on the inverted wings and a pulley system used to try and raise the aircraft fuselage, thus simulating an aerodynamic lifting force on the wings. A number of early flying accidents in biplanes were actually caused by wing struts collapsing during diving manoeuvres. It was only subsequently realised, rather counter-intuitively, that the upper wing could produce a crushing force in such circumstances able to induce this type of failure, and stressing calculations had to be modified accordingly to compensate.³⁹ This example really illustrates the developmental nature of aeronautical engineering at the time, and one woman in the thick of this evolution in structural analysis was mathematician Hilda Hudson.

4 Hilda Hudson

Hilda Hudson was born into mathematics. Her father, William, lectured in mathematics at Cambridge and was subsequently appointed Professor of Mathematics at King's College, London, shortly after Hilda's arrival into the world in 1881. Her mother read mathematics at Newnham College, Cambridge, and her elder brother excelled at St John's, Cambridge, achieving the coveted accolade of Senior Wrangler in the Mathematical Tripos of 1898; her sister would, very creditably, be ranked alongside the equal-eighth Wranglers on the list of 1900. What pressure, then, on Hilda to shine when she arrived at Newnham in that same year. Like her family before, however, she rose to the challenge and held bragging rights over her sister by achieving a mark equivalent to the seventh Wrangler on the list of 1903, following Part I



Figure 2: Hilda Hudson

³⁷ The Pembroke College, Cambridge, Wrangler and Rayleigh Prizeman, Frazer, had been employed at the NPL working on viscous flow problems, but was drawn into the flutter debate by Fage and Bairstow, and it would become a lifelong distraction. One of the most important structural modifications he devised was the use of mass balances on ailerons to help prevent wing flutter (Pugsley, 1961).

³⁸ A comprehensive collection of original notes detailing many of the destructive tests conducted by Thurston and his team based at the East London College can be found in the John Turner MacGregor archive at Queen Mary University, London (archive reference, PP29).

³⁹ The dive and increasing speed induced an aerodynamic twisting action in the aerofoil as the centre of pressure moved rapidly rearwards. Rather than act to pull the wing off, the rearward position of the lift vector could sometimes act in such a way as to create a rotational moment that placed an excessive crushing force on the front struts, leading to structural failure.

of the Mathematical Tripos examinations. A year later she took Part II of the Tripos and was placed in the third division of the First Class.⁴⁰

After leaving Cambridge in the summer of 1904 she spent the winter semester at the University of Berlin where she attended lectures given by Hermann Amandus Schwarz, Friedrich Schottky, and Edmund Landau.⁴¹ It is likely that Schwarz and his colleagues were major influences in developing Hudson's interest in conformal transformations, a topic initially introduced to her by Arthur Berry during her time at Cambridge, and one that would eventually dominate her mathematical research, which culminated in 1927 with the publication of her comprehensive and well-respected treatise, *Cremona transformations in plane and space* (Hudson, 1927).

One must certainly wonder what forces and influences were at play in fostering Hudson's move to Berlin. She would have been encouraged by her family no doubt, and Berry certainly had relevant contacts and experience, having previously taken a sabbatical at Göttingen university to work with Felix Klein, and also having coached Grace Chisholm Young at Girton prior to her doctoral work under Klein at Göttingen.⁴²

Her return from Germany saw her back at Cambridge, first as a lecturer at her alma mater and later as an Associate Research Fellow. Hudson's letter of application for the Fellowship offered by Newnham College in 1910 is most revealing, particularly regarding Berry's involvement. Not only do we learn that Hudson met with Berry on numerous occasions in the early part of that year, but she makes it quite clear that he was the one who suggested the line of research she proffered in her application.⁴³ Furthermore, it would be Berry to whom Eleanor Sidgwick, the College Principal and recipient of Hudson's application, would turn for advice as to the merit and potential of Hudson's proposed research; unsurprisingly, Berry was most supportive, and on news of her subsequent appointment to the post remarked to Sidgwick, "I feel sure you have chosen a very good Fellow!"⁴⁴

Perhaps a defining moment in Hudson's life came in 1912 when she became the first woman to deliver a communication (Hudson, 1912) at the International Congress of Mathematicians (ICM).⁴⁵ A short spell at Bryn Mawr College pre-

⁴⁰ For a detailed description of development and structure of the Mathematical Tripos, see Andrew Warwick's book *Masters of Theory* (Warwick, 2003).

⁴¹ Schottky had succeeded Lazarus Fuchs at the University of Berlin in 1902, and the former's doctoral thesis, published in 1877, was considered an important contribution in the field of conformal mappings; indeed, much of his post-doctoral work was concerned with linear transformations. Schwarz, at the university since the departure of Weierstrass in 1882, also had strong links with conformal mappings. Issai Schur, too, was lecturing in Berlin whilst working on the projective representations of groups during Hudson's stay in the city.

⁴² See Ch.6. of Claire Jones' *Femininity, Mathematics and Science, 1880-1914* (Jones, 2009).

⁴³ Hudson's proposal, detailed in a letter, dated 30th April 1910, and held in the Newnham College archives, was entitled *Birational Transformations in Three Dimensions*, and looked to improve and develop work done previously by Arthur Cayley (Cayley, 1870) and Corrado Segre (Segre, 1897).

⁴⁴ Quote taken from a letter, dated 1st June 1910, from Berry to Sidgwick, which is held in the Newnham College archives.

⁴⁵ Interestingly, Hudson's pioneering status may have been assumed by the Italian mathematician, Laura Pisati, at the ICM meeting in Rome 4 years earlier. The latter's untimely

ceded her appointment as a lecturer in mathematics at the West Ham Municipal Technical Institute, London, which coincided with the advent of its Junior Engineering School for Boys.⁴⁶ Hudson resigned from her research fellowship at the end of March 1913, two months before its formal conclusion, to facilitate the move to London.

The exact reason Hudson decided to leave her teaching post in 1917 and join the civil service is unclear, but the government had been actively running recruitment drives to draw women into the vacuum created in the traditionally male-dominated professions by conscription, which had been introduced for men in 1916.⁴⁷ She was immediately drafted into the Admiralty to mentor a group of women that would become an essential cog in the wheel of the Stressing Section of the Structures office.⁴⁸ She was slightly older and more experienced than most of her female colleagues and had the presence and work ethic to set a fine example, soon earning herself the title of Sub-section Director.⁴⁹ She also demonstrated her mathematical flexibility, temporarily casting aside her passion for, and expertise in, geometry to enter the applied world of moments, stresses and strains.

In addition to acting as the linchpin between the key men in the department (Berry, Pritchard and Pippard) and the women assigned to assist them, Hudson would individually author two notable pieces of work that were published after the War, as are now described.

4.1 The Strength of Laterally Loaded Struts

The first article, ‘The Strength of Laterally Loaded Struts’, appeared in *Aeronautical Engineering* in June of 1920 (Fig. 3) (Hudson, 1920b).

Hudson’s starting point was the knowledge that the formula often employed for the calculation of the strength of wing struts subjected to both lateral and axial loads could, in certain cases, give incorrect results as the proportion of bending to compression was reduced; indeed when the lateral load became very small, the formula became worthless.⁵⁰ In this piece of work she first elaborates on the extant methodology, before suggesting her modification.

If a strut is absolutely straight and uniform and under a perfect axial end load,

and premature death just prior to the 1908 Conference, however, led to her paper being read by a male delegate, Roberto Marcolongo, as described by Furinghetti (Furinghetti, 2008, 533-534).

⁴⁶ Situated in the East End of London, West Ham Municipal Technical Institute opened in 1900 to provide courses in Science, Engineering and Art for boys. Later, secretarial and trade courses for girls were added and eventually, in 1913, came the Junior Engineering School for Boys. It was the seedling of what has now grown into the University of East London.

⁴⁷ The Military Service Act of March 1916 imposed conscription on all single men in Britain between the ages of 18 and 41 (with some exemptions, including ‘conscientious objectors’); a second Act in May of that year extended the net to include married men.

⁴⁸ One might conject that Berry may have been a broker in this appointment.

⁴⁹ Chitty described Hudson as a “terrific worker” (Chitty, 1966, 67).

⁵⁰ Hudson was particularly interested in parallel, pin jointed struts subjected to a uniformly distributed side load in addition to compression, as would be found between the wings of a typical biplane.

THE STRENGTH OF Laterally Loaded STRUTS.

By HILDA P. HUDSON, O.B.E., M.A., Sc.D.

The formulæ usually employed for the calculation of the strength of members subjected to both lateral and axial loads may, in certain cases, give more and more erroneous results as the proportion of bending to compression is reduced, and may break down altogether if the lateral load is small.

To illustrate the argument I shall consider parallel pin jointed struts subjected to a uniformly distributed side load in addition to compression. If the strut is perfectly straight, uniform and axially loaded one can write :

$$py = \frac{PN}{A} + \frac{MN}{Z} \sec \alpha - 1, \left(\alpha = \frac{\pi}{2} \sqrt{\frac{PN}{P_E}} \text{ radians} \right), (1)$$

where py = yield point of the material,

P = unit compressive load,

N = load factor,

A = area of section,

M = unit maximum bending moment due to distributed load alone,

Z = strength modulus in direction of failure,

I = moment of inertia of section,

l = length,

P_E = Eulerian failing load.

It is, however, more useful to resort to Professor Perry's approximation to the above, viz. :

$$py = \frac{PN}{A} + \frac{MN}{Z} \frac{1}{1 - \frac{PN}{P_E}} (2)$$

Everything else being known, this form can be used to calculate the load factor by reducing to a quadratic in N . Now put $M=0$ in equation (2), whence :

By putting $M=0$ in the above equation :—

$$py = \frac{PN}{A} + \frac{P_0 N}{Z} \frac{1}{1 - \frac{PN}{P_E}}, (7)$$

and by reduction this will be found to be identical with Professor Perry's modification of Professor Smith's formula for the strength of a pin-jointed strut as quoted by Southwell.⁵¹

Conversely, if the failing load P is read from a curve, found by experiment or otherwise known, then equation (7) gives the equivalent eccentricity of loading that is consistent with this estimate, and which should be used if the strut is afterwards subjected to side load.

It will be clear that a member calculated on the usually accepted Perry formula may have a smaller strength factor than is supposed.

Of course, it may happen in any particular case that the extra bending moment set up by the initial eccentricity acts against the applied bending moment and so strengthens the member. Since, however, nothing is usually known as to the plane of δ , the only safe course is to assume the worst case in which M and P_0 are additive. Since the two planes are equally likely to be at any angle, the correction does not show in an average of a large number of test results, but rather in the deviation of individual results from the average.

The percentage reduction of factor with a given assumption of eccentricity will depend upon $\frac{l}{k}$ and upon the proportion of axial to bending stress.

Figure 3: The Strength of Laterally Loaded Struts

it will theoretically fail when the end load reaches the smaller of its elastic compressive strength (pyA) or its Euler failing load (P_E).⁵¹

In practice, however, it was known that this theoretical value applied only to extremely short or extremely long struts. William Macquorn Rankine had realised this long before struts had aeronautical applications,⁵² and another sagacious, more contemporary, character who empathised was Richard Southwell (1888-1970) who devised, by experiment, a measure of 'equivalent eccentricity' that could be introduced into the standard equation as a compensatory factor (δ).⁵³

In 1886, prior to Southwell's insight, some of John Perry's lecture notes on the subject of struts had appeared in the weekly technical publication, *The Engineer* (Perry and Ayrton, 1886).⁵⁴ Perry's equation derived therein was

⁵¹ Elastic compressive strength is the product of the yield point, py , and area of cross-section, A . The Euler failing load was derived by Leonhard Euler by applying the calculus of variations to elasticity theory, and his equation, which was published in 1744 (Euler, 1744, 267), defines the maximum axial force, P_E , that can be applied to a long, slender, straight, homogeneous beam, before it buckles:

$$P_E = \frac{(\pi)^2 EI}{(KL)^2}$$

Where E =Young's modulus; I =area moment of inertia; KL =effective beam length (K 's value reflecting the status of the end points of the beam, fixed or pinned).

⁵² Rankine is perhaps best known for his work in thermodynamics, but also held a professorship in Civil and Mechanical Engineering at the University of Glasgow; he died in 1872.

⁵³ For Southwell, see Section 5 and footnote 66.

⁵⁴ Perry had prepared four lectures that he delivered to the second year Mechanical Engineering students at Finsbury Technical College during the Spring of 1886. The article that appeared in *The Engineer* was co-authored by William Ayrton, Professor of Applied Physics at the College.

TABLE II. Percentage Reduction of Load Factor for Continuous Beams.									
C.	L/k.								
	20	40	50	60	70	80	100	120	140
0.1	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0	9.0
0.2	1.0	2.5	3.5	4.0	6.0	8.5	16.0	50.0	—
0.3	2.0	4.5	6.0	9.0	12.0	18.0	72.0	—	—
0.4	2.5	6.0	9.0	14.0	23.0	43.0	—	—	—
0.5	3.5	8.0	14.0	23.0	44.0	—	—	—	—
0.6	4.0	11.0	20.0	39.0	63.0	—	—	—	—
0.7	5.0	15.0	31.0	63.0	—	—	—	—	—
0.8	6.0	23.0	50.0	80.0	—	—	—	—	—
0.9	7.0	41.0	77.0	—	—	—	—	—	—

Figure 4: Hudson's Correction Table

Hudson's opening gambit:

$$py = \frac{PN}{A} + \left(\frac{MN}{Z} \right) \left(\frac{1}{1 - \frac{PN}{P_E}} \right)$$

She was interested in establishing more realistic values for the load factor (N) given values for the yield point of the material (py), the unit compressive load (P), the cross-sectional area (A), the maximum bending moment due to distributed load alone (M), the modulus of strength in the direction of failure (Z), and the Eulerian failing load (P_E) discussed earlier. Introducing Southwell's (δ) modified Perry's equation to define a reduced load factor (N_1), thus:

$$py = \frac{PN_1}{A} + \left(\frac{(M + \delta)N_1}{Z} \right) \left(\frac{1}{1 - \frac{PN_1}{P_E}} \right)$$

Despite this modification, there was still a lack of consistency in theoretical calculations versus experimental results. The reason was that maximum bending moment due to distributed load alone, (M), could be exacerbated or, equally, relieved by any eccentricity present; so values for (δ) derived from experimentation were often erroneous. Hudson wanted to impose a further constraint on load factors to cater for worst-case scenarios, and so introduced three new variables; her safety factor would depend on the quotient of strut length, (L), and its least radius of gyration, (k), and upon a measure of the direct stress on the strut, (C).⁵⁵

Fig. 4 shows Hudson's final correction table, where (C) is read vertically, and (L/k) horizontally. For example, if (C)=0.6 and (L/k)=70, then the required percentage reduction in load factor would be 63%. Rather disappointingly, however, after all her deliberation and reasoned argument, Hudson's conclusion is rather hand-waving because she admits that eccentricity is actually so ill-determined that, in reality, all her numerical values are rather arbitrary, and

⁵⁵ C is defined as the quotient of PN and pyA .

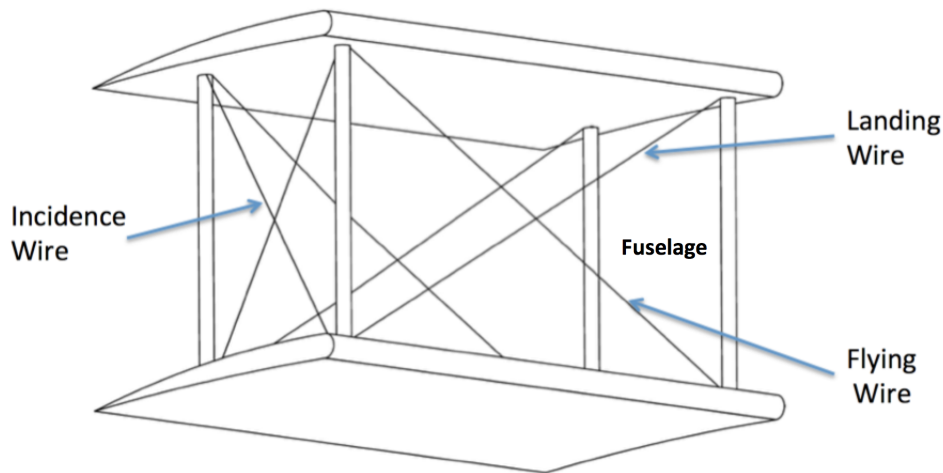


Figure 5: Aircraft Rigging Wires

that all one can really take away from the work is that some allowance should be made, and that any such allowance might be appreciable!

4.2 Incidence wires

Her second piece, ‘Incidence Wires’, appeared in the *Aeronautical Journal* in 1920 (Hudson, 1920a).

To be clear about the function of incidence wires, we need to consider three of the general classifications of wires these early aircraft employed. Wires that worked against the wings as they provided normal lift in flight were called *flying wires*, and wires that held the wings up on the ground and supported the wings during landing impact were known as *landing wires*. The wires that ran diagonally between fore and aft struts were known as the *incidence wires*, and were in place to prevent the wing sections twisting relative to their mountings at the fuselage or relative to each other in the case of biplanes and the later triplanes (See Fig. 5).⁵⁶

Traditionally, aeroplanes had been treated as braced structures containing a number of redundant members that were not included in any initial strength calculations. In her summary of this paper, however, Hudson emphasises the serious increase in load on the lower wing of a biplane during a nose dive. This was the justification for insisting on a second approximation that took account of the redistribution of load in such circumstances. Hudson’s important work focused on calculating the strains in the incidence wires under various flight modes: level flight, in a nose dive, and in the situation where another wire may have been severed by some mechanical failure or as a result of enemy action.

⁵⁶ A fourth classification of wires, *control wires*, existed to enable the pilot to move flying control surfaces such as elevators, ailerons, rudders etc.

The mathematics of these calculations centres around a method of ‘least strain energy’, relying on the fact that, as Hudson puts it,

... for strains within elastic limits, the loads in any redundant members take up such values as make the total strain energy of a connected system a minimum (Hudson, 1920a, 506).

She derives an expression for the total strain energy:

$$\sum \left(\frac{l^3}{2EA} \right) (p_0 + p_1 t_1 + p_2 t_2 + \dots + p_n t_n)^2$$

Parameters of length (l), cross-sectional area (A), and modulus of elasticity (E) for any given wire appear in the formula; the expression $(p_0 + p_1 t_1 + p_2 t_2 + \dots + p_n t_n)$ represents the tension per unit length in any given wire as a function of the load induced in that wire by any external forces when all (n) redundant wires are slack, (p_0), plus the potential load contributions in any given circumstance from each of those redundant wires, ($p_1 t_1$) etc. Hudson uses (Σ) in a rather confusing way to indicate the total strain energy of the system being considered.

Partial differentiation of her expression for strain energy with respect to (t_1), (t_2), ..., (t_n), in turn, produces a set of (n) partial derivatives that she is justified in setting to zero to define the minimum energy state, and which can then be solved simultaneously.

$$\sum \left(\frac{l^3}{EA} \right) p_1 (p_0 + p_1 t_1 + p_2 t_2 + \dots + p_n t_n) = 0$$

$$\sum \left(\frac{l^3}{EA} \right) p_2 (p_0 + p_1 t_1 + p_2 t_2 + \dots + p_n t_n) = 0$$

\vdots

$$\sum \left(\frac{l^3}{EA} \right) p_n (p_0 + p_1 t_1 + p_2 t_2 + \dots + p_n t_n) = 0$$

In the remainder of her paper, Hudson takes the reader through various numerical examples that illustrate the application of this technique to different wing configurations. The origin of this method of calculation has an appropriate, if tenuous, link to Hudson herself, and can be traced back to Turin.

4.3 Castigliano

It was the Italian mathematician Alberto Castigliano (1847-1884), in his 1873 dissertation *Intorno ai sistemi elastici* (*Concerning Elastic Systems*) (Castigliano, 1873), who first postulated the method of using partial derivatives of strain energies in calculations such as those being employed by Hudson. He built on previous groundwork completed in this field by the Frenchman and thermodynamicist Emile Clapeyron in the 1820s and, more contemporarily, by compatriot

Luigi Menabrea.⁵⁷ Regretably, however, there ensued a rather bitter priority dispute between Castigliano and his fellow Italian regarding this work, since Menabrea’s ‘energy method’ concept lay at the heart of Castigliano’s more mature offering. This spat prompted a special meeting of a committee of the Accademia dei Lincei, chaired by Luigi Cremona (1830-1903), whose birational transformations inspired Hudson’s defining work.⁵⁸ Sadly, Cremona’s death coincided with Hudson completing her degree, so he would never witness her post-war homage.

4.4 Sutton Pippard

Adding to this mathematically incestuous web, it is documented that Hudson’s mentor, Sutton Pippard, had drawn great inspiration from Castigliano’s work whilst studying for his degree at Bristol University, and so he may well have schooled Hudson in the nuances of the Italian’s stress analysis techniques (Skempton, 1970, 464). Pippard had been appointed as technical adviser to the Director of the Air Department of the Admiralty in 1915. He soon established himself as a key figure in the field of structural analysis, and he would go on to become an influential figure at Imperial College.⁵⁹ His key legacy from the war years was to co-author two books with J.L. Pritchard, the *Handbook of Strength Calculations* (Pippard and Pritchard, 1918), and *Aeroplane Structures* (Pippard and Pritchard, 1919), the latter described in *Nature* (Brodetsky, 1921a) as:

... an authoritative account of one of the most important aspects of aeroplane design, as well as aeroplane theory, and will no doubt be the standard work on the subject in English for some considerable time.⁶⁰

This bold prophecy proved insightful as the work did, indeed, become the standard text for interested parties throughout the inter-war years, appearing in a revised edition as late as 1935. Pippard would also have a significant influence on the second of the women under the spotlight in this story, Letitia Chitty.

⁵⁷ Menabrea, Professor of Mechanics and Construction at both the Military Academy of the Kingdom of Sardinia and at the University of Turin achieved posthumous notoriety as the author of *Notions sur la machine analytique de M Charles Babbage*, an account of Charles Babbage’s lectures of 1840 at the Turin Academy of Sciences outlining the workings of his Analytical Engine (Menabrea, 1842). Ada Lovelace, daughter of Lord Byron and friend of Babbage, famously translated Menabrea’s text (between 1842 and 1843), and added her own set of elaborate comments she simply called *Notes* (Lovelace, 1843). This additional commentary contains what many identify as the first ever computer program.

⁵⁸ Bruno Boley gives a full account of this story in his entry for Castigliano in the *Complete Dictionary of Scientific Biography* (Boley, 2008).

⁵⁹ Imperial College holds Pippard’s personal archive under the reference CSAC 97/1/84.

⁶⁰ Selig Brodetsky (1888-1954), joint Senior Wrangler in 1908 and author of the review in question, was an influential figure in aerodynamics in Britain during the first half of the 20th century, establishing himself at the University of Leeds where he filled the Chair of Applied Mathematics, 1924-1948. His post-war work *The Mechanical Principles of the Aeroplane* (Brodetsky, 1921b), however, attracted some rather polarised reviews (Aubin and Goldstein, 2014, 108). Less controversial was his book on nomography (Brodetsky, 1920), which complemented earlier work by d’Ocagne (1862-1938) in France; see footnote 71.

5 Letitia Chitty

In 1914, as war began to rage in Europe, Chitty, aged seventeen, was busy working with her private tutors in Winchester. Unlike Hudson, she was not surrounded by a family of mathematicians, but they were academically minded, with a particular affiliation to Balliol College, Oxford.⁶¹ Two years later her diligence paid dividends and she went up to Newnham to read mathematics. Her talent for the subject soon became apparent, and as demand grew in London for competent mathematicians to assist with the war effort, it was agreed that Chitty would be released at the end of her first year at Cambridge with the promise that she could resume studies once war was over.

Rumours of Hudson's work at the Admiralty had already filtered back to Newnham via the dons' network, so that was where Chitty wanted to be. By a somewhat convoluted route, in August 1917, the now twenty-year-old Chitty presented herself at the Hotel Cecil. She was allocated a shared room with two women already working for Hudson, Dorothy Chandler and Mary Hutchison, and soon encountered Beatrice Cave-Browne-Cave who was then working alongside Eleanor Lang for Leonard Bairstow, who had himself recently moved to the Admiralty.⁶²



Figure 6: Letitia Chitty

Quotes, all taken from Chitty's later recollections of her time at the Admiralty, give us some insight into the mathematics and mathematical methods being employed, and general modus operandi of the Stressing Section at that time.⁶³

We relied upon our slide rules and arithmetic in the margins, supported by the theorem of 3 moments and Southwell's curves for struts.

The 3 moments theorem here refers to Émile Clapeyron's work in the middle part of the 19th century which addresses the relationship between the bending moments at three consecutive supports of a horizontal beam. In its raw state, the theorem's application to aircraft structures was awkward; Arthur Berry, however, managed to adapt it into a more user-friendly form for wing spar calculations, his 'Berry Functions' now legendary in the world of stress analysis.⁶⁴

⁶¹ Her father, Herbert, studied Classics at Balliol and eventually became the archivist at Winchester College; he was considered worthy of recognition at the National Portrait Gallery, London, where a print hangs of him playing cards in later life. Her elder brother, Christopher, also attended Balliol before being ordained.

⁶² Dorothy Chandler graduated with a BA Honours degree in Mathematics from Royal Holloway College in 1910, having first studied for the Intermediate Arts exam which covered Latin, English and Pure and Applied Mathematics. Mary Hutchison was a product of the East London College, graduating in 1913 with a BSc Honours in Mathematics; both arrived at the Admiralty a week before Chitty.

⁶³ Chitty contributed to the centenary edition of *The Royal Aeronautical Society's Journal* in 1966 (Chitty, 1966, 67-68); all quotes used here are taken from these reminiscences.

⁶⁴ Berry functions are tabulated values of awkward, trigonometric expressions that appear as coefficients in moment calculations; they are listed, for example, in an Appendix to

Arguably, Berry was the strongest mathematician working for the Admiralty at this time and he, like Pippard, would have had a significant influence on those working with him.⁶⁵ The ‘Berry Method’ became mandatory for calculating main spar loading for any aircraft wanting Air Ministry approval, since it took a more rigorous approach than its alternatives.

Richard Southwell had been schooled at Trinity, Cambridge by Bertram Hopkinson, and his postgraduate interests centred around elastic stability in structures. He had already published work in this area and had just taken up post as a lecturer at Trinity when war broke out.⁶⁶ The “curves” mentioned by Chitty (see Fig. 7) illustrate the contemporary preference for mathematical equations to be presented in a more accessible, graphical form.⁶⁷ The example shown simply requires knowledge of the length and diameter of the strut in question to glean an approximation for the relevant crippling load.

Each aeroplane, designed but not yet constructed, was received in the form of drawings and assigned to a pair of workers, the one to stress, the other to check the calculations ... lives were at stake!

This observation tells us much about how different things were in those early days of aviation regarding the process of producing new aircraft. Nowadays, stress analysis is an integral and iterative part of the design process from conception; in 1917 it was necessarily more haphazard due to the incessant pressures of the War, although the appreciation that the lives of aircrew were at the mercy of the accuracy of the mathematical calculations being done by these women was clearly not lost on them.

The general conditions for stressing were normal flight, nose diving, and ‘wires cut’ one at a time.

Here we have Chitty’s confirmation of Hudson’s earlier description of the specific modes of flight considered for stress analysis at the Admiralty.

To begin with Captain Pritchard did most of the teaching; later we taught the newcomers!

At the end of the War, as a joint effort, we wrote the *Handbook of Strength Calculations*.

(Pippard and Pritchard, 1918). The user simply has to look up the relevant value in a table using an angle value as the argument. A typical Berry Function with argument α might be:

$$\phi(\alpha) = \left(\frac{3}{4}\right) \left(\frac{1 - 2\alpha \cot 2\alpha}{\alpha^2}\right)$$

⁶⁵ Pippard described Berry as “... an exceptional professional mathematician.”, but was amused by the latter’s lack of exposure to practical engineering. He recalls the occasion when Berry, the Vice-Provost of King’s, enquired about an “odd instrument” being used in the office; apparently he had never previously encountered a slide rule (Pippard, 1966, 70)!

⁶⁶ Southwell’s initial work on struts was published in the *Engineer* in 1912 (Southwell, 1912), and he followed this up with further work investigating the failure of metal tubes and formulating a general theory for elastic stability (Southwell, 1913, 1915).

⁶⁷ Fig. 7 is an example of an *intersection nomogram*, one of two types of nomogram in use at the time, the other being an *alignment nomogram*, a good example of which can be seen at Fig. 10.

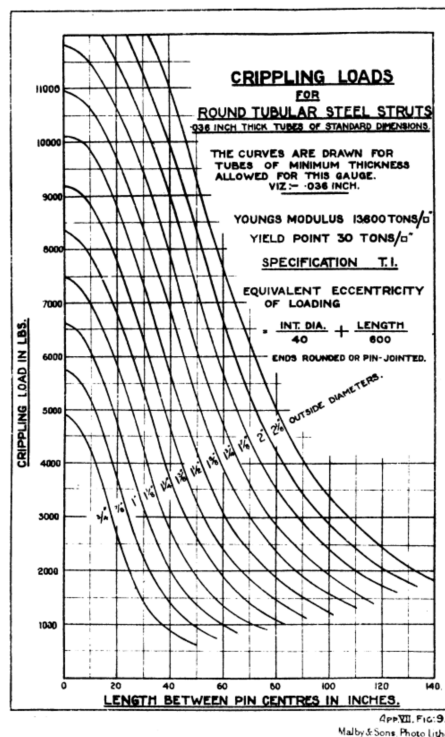


Figure 7: Southwell Curves for Crippling Loads.

So, despite Pippard and Pritchard grabbing the headlines for running the department and producing the seminal text describing aeronautical strength calculations, clearly there was a camaraderie present that fostered trust and collaboration. The task facing the department as the air battles intensified must have been huge, so one cannot overemphasize the importance of such teamwork in coping with the burgeoning number of new aircraft being designed and requiring certification. To put this in context, in the year 1914, the number of aircraft produced in Britain was in the low hundreds; by the time peace was brokered in 1918, annual production had risen to over 30,000.

It is worth emphasising that sole authorship of ACA technical publications was not de rigueur for women at that time, so any granted this honour were exceptional; they were, however, more frequently given credit in a joint capacity. We have already seen that Hudson's individual efforts were published, but in journals rather than as ACA Technical Reports. Of course much of the work on stress analysis was 'classified' during the War itself, which explains why some of it did not appear in the public domain until the 1920s and beyond.

It is clear that Letitia Chitty had been inspired by Sutton Pippard during her time working in the Stressing Section, and there was certainly an element of mutual respect.⁶⁸ So much so, after the War, Chitty returned to Cambridge and

⁶⁸ Pippard said of Chitty, "She was not just a methodical calculator, but a good theoretician

immediately transferred from mathematics to engineering, later being placed in the First Class in the Mechanical Sciences Tripos, the first woman ever to achieve this distinction. She would later team-up with Pippard to undertake stress analysis on all manner of objects, including arches, wheels, dams, and extensible cables.⁶⁹ Prior to this symbiotic collaboration she also found occasion to work with both Bairstow and Southwell, the latter on hydrodynamic stability (Southwell and Chitty, 1930), and stresses in airship hulls (Chitty and Southwell, 1931), demonstrating her remarkable flexibility and giving a clear indication of the lasting impression she must have made during her time at the Admiralty.

6 Beatrice Cave-Browne-Cave

Beatrice Cave-Browne-Cave⁷⁰ was educated at home and, like Hilda Hudson, blessed with siblings around her who shared her passion for mathematics. She would eventually go up to Girton in 1895 and come away in 1899, having been placed in the Third Class in Part II of the Mathematics Tripos, perhaps, with hindsight, a rather modest indication of her mathematical potential. She immediately took one of the few options open to female mathematicians and became a teacher at Clapham High School, but it would be an opening at UCL just before war began that would launch Cave-Browne-Cave's career in mathematics. Her sister Frances was employed as a mathematics lecturer at Girton, but had established a concurrent working relationship with Karl Pearson in London (see footnote 31), and so likely played some part in Beatrice's appointment. Beatrice's initial work was statistical in nature but, as the War intensified and much to Pearson's chagrin, she took an opportunity to earn more money by working at the Admiralty on aircraft tail loading analysis and the study of aircraft oscillations.



Figure 8: Beatrice Cave-Browne-Cave (Image taken from: *The Mistress and Fellows*, Girton College, Cambridge)

We see in Figs. 9 and 10, two of the original diagrams used by Cave-Browne-

in her own right. She should have been encouraged to publish more on her own, and should, perhaps, have been given a professorship.” (Gay, 2007, 187).

⁶⁹ Pippard was placed in charge of the Civil Engineering Department at Imperial College in 1933, and was reunited with Chitty when she was appointed his Research Assistant in the following year; thence began their fruitful academic partnership, as witnessed by the many subsequent joint publications spanning the years 1936-1960, which are listed in (Skempton, 1970, 477-478).

⁷⁰ The interesting history behind the evolution of Beatrice's rather distinctive surname dates as far back as William the Conqueror who, in 1069, conferred upon two brothers living in the English county of Yorkshire, the Lordships of South and North Cave. The *Baronetage of England* (Kimber and Johnson, 1771, 355-365) relates the story of the Caves until the mid-1700s, and also illustrates their coat of arms (Kimber and Johnson, 1771, A6). Cokayne's *Complete Baronetage* (Cokayne, 1902, 93-95) picks up the narrative, explaining the change by Act of Parliament to *Cave-Browne* in 1752 and, by Royal Licence, to *Cave-Browne-Cave* in 1839.

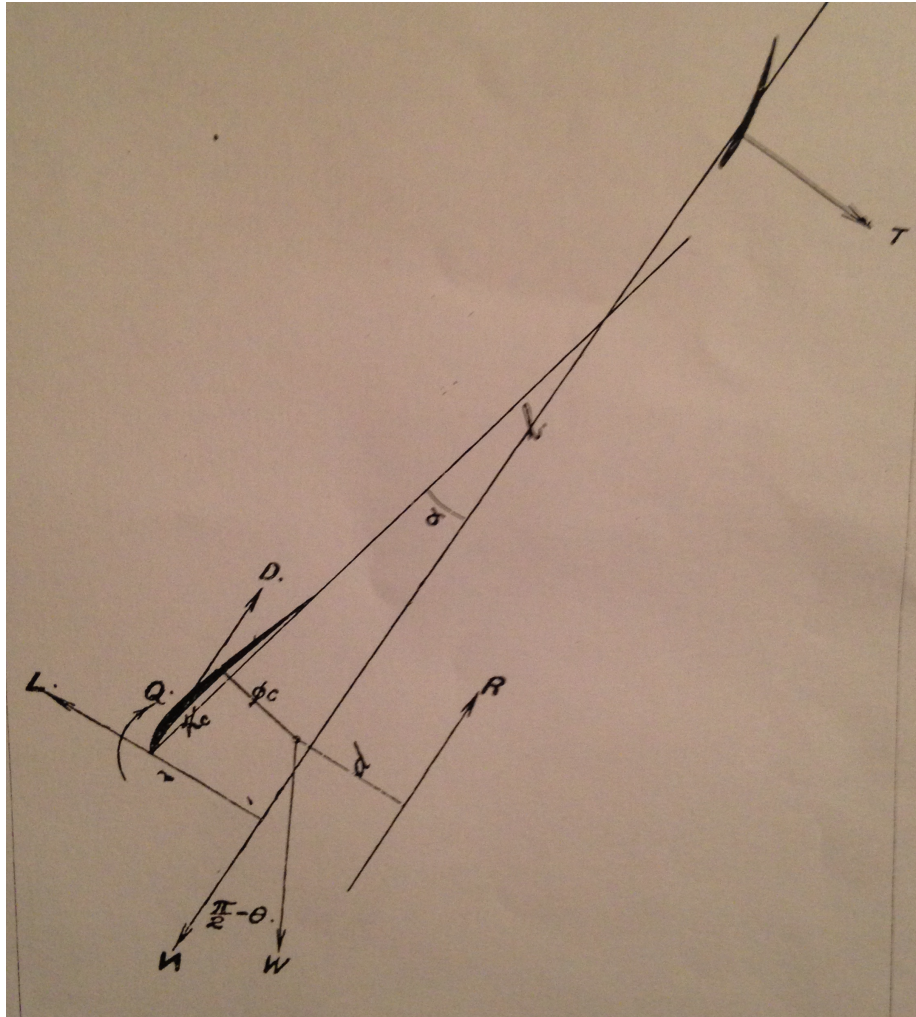


Figure 9: Force diagram.

Cave to calculate the force on a tailplane. Fig. 9 is her force diagram and Fig. 10 depicts her use of an alignment nomogram, a device employed when a single type of calculation had to be done repeatedly, and invented by the French engineer Philibert Maurice d'Ocagne in 1884 in response to a demand by French engineers for a method to speed up the operations of cut-and-fill necessary to expand France's railway system.⁷¹

To use this particular nomogram she would have started with the input of *Weight of Machine* on the left (3000 lbs) and constructed the straight line that connects to the *Main Plane Chord* (6 ft); this line then defines a point on the reference line through which a second straight line is constructed from *Distance from Centre of Gravity to Tail Plane* (15 ft) to intersect the *Tail Load* scale,

⁷¹ Maurice d'Ocagne would go on to write a number of treatises on the study of nonomgraphy and other types of graphical calculating methods following his collection and analysis of both intersection and alignment nomograms; see (Tournès, 2016).

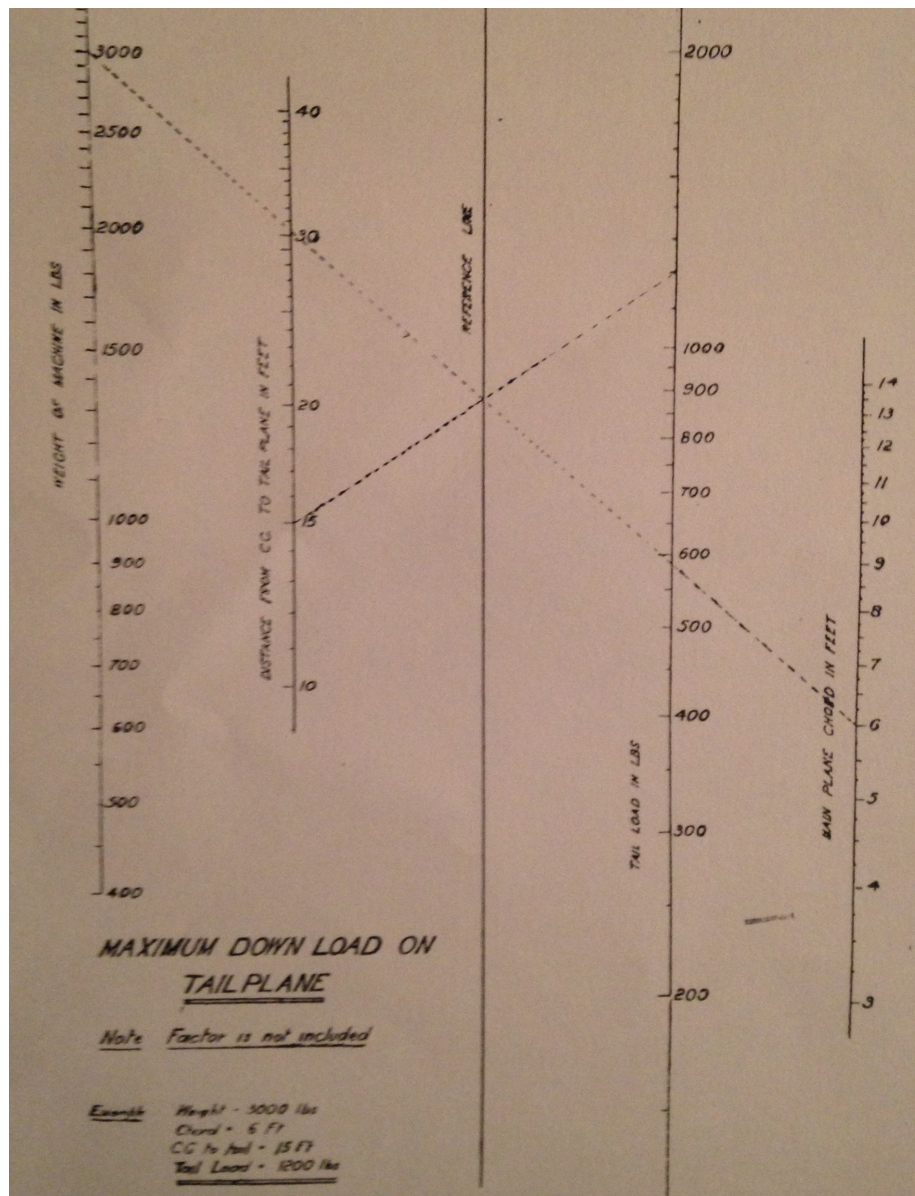


Figure 10: Alignment Nomogram.

from which the load on the tail can be read off (*1200 lbs* in this case). Clearly this is a simple method of calculation for anyone averse to algebra or slide rules so would have been welcomed in industry.

Her study of aircraft oscillations was published in an ACA Technical Report (Cave-Browne-Cave, 1922), and demonstrated her sound grasp of the necessary mathematics. As the War ended, Leonard Bairstow, who was moving to become the first Zaharoff Professor of Aerodynamics at Imperial College, asked Cave-Browne-Cave and Lang to assist him with research into objects moving in viscous

fluids, and both women would be acknowledged in the final published papers (Bairstow et al., 1922, 1923). The mathematics here is rather complex; quite how much of it was developed by Bairstow versus his assistants is not clear. It is likely that the women would have been employed to check Bairstow's work and also develop pieces of original mathematics delegated to them by Bairstow that he could subsequently incorporate into the general flow of the proofs. Either way, transitioning into the field of fluid dynamics from that of stress analysis shows great mathematical flexibility on the part of Cave-Browne-Cave.

7 Conclusion

Engineering mathematics was not a field populated by an abundance of women in the early 1900s; there was little societal precedence, encouragement or support for it to be otherwise. Hudson, Chitty and Cave-Browne-Cave, however, certainly stand out as clear examples of women who swam against the prevailing tide of prejudice and conventional expectation. They all benefited from familial stimuli and resource, which were almost obligatory prerequisites for any young woman aspiring to go up to Newnham or Girton, but infringing the male-dominated world of mathematics also demanded certain intrinsic qualities. These women had minds capable of original and independent mathematical thought, coupled with the strength of character to overcome the tradition standing in their way.

We only need look at Hudson and her treatise on Cremona transformations or Chitty and her later eminence and expertise in the field of stresses in arches and dams to find proof of the natural mathematical talent these women possessed. Indeed, in writing the former's obituary in the *Bulletin of the London Mathematical Society* (Semple, 1969, 358), the respected algebraic geometer, J.G. Semple, lauded Hudson as:

... a distinguished mathematician, of great erudition and integrity.

Their mathematical flexibility was also testament to their broad understanding of the subject. Hudson, a geometer at heart, tackled applied mathematics to help the war effort. Cave-Browne-Cave engaged in statistical analysis with Karl Pearson and transitioned to stress analysis with Sutton Pippard. Chitty made the switch from mathematics to the mechanical sciences at Cambridge to become a respected civil engineer.

They were also ground breakers: Hudson, the first woman to deliver a paper at an ICM; Chitty, the first woman to be placed in the First Class in the Mechanical Science Tripos; Cave-Browne-Cave, one of the first to sole-author an ACA Technical Report.

Objectively, much of the mathematics these women were doing whilst working for the Admiralty during the War could not be described as exceptional, but it was certainly necessary. With each new design of aircraft came the concomitant demand for the calculations that would determine its structural integrity and limitations. Without competent and dedicated mathematicians the new breed of industrial aeronautical engineers would have been exposed to relying entirely

on the rather blunt tools of judgement and experience. That said, whilst the bulk of the mathematics was well-established, its specific application to aircraft was not; here lay the challenge.

The pathway leading to a career in applied mathematics outside of education for female mathematicians in those early days of fixed-wing aeronautics, as we have seen, was strewn with all manner of obstacles, but Hudson, Chitty and Cave-Browne-Cave negotiated them admirably. Did the demands and urgency of the War assist their career progressions? Probably; the conflict certainly created an employment vacuum as men were taken in ever-increasing numbers by conscription, but these women certainly seized their opportunities to infiltrate the male bastion of engineering. Their calculations, expertise and diligence will certainly have prevented many unsafe designs moving from drawing board into production; this was their practical legacy. However, these women represented more than just a technical check and balance in the chain of aircraft design and production. They were pioneers who demonstrated that it was possible for women to overcome the dogmatic, institutionalized prejudices of the time, and they earned the right to stand tall as credible applied mathematicians during the genesis of aircraft stress analysis.

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